INFLUENCE OF DAMAGE ON THE VIBRATION RESPONSE OF COMPOSITE LAMINATES

Milan Mitrovic & Greg P. Carman
Mechanical, Aerospace & Nuclear Engineering Department
University of California Los Angeles

Gail A. Hickman
Innovative Dynamics, Inc.
Ithaca, New York

Yoseph Bar-Cohen
Jet Propulsion Laboratory., Caltech
Pasadena, California

ABSTRACT

The influence of delaminations on the natural frequencies and mode shapes of a composite laminate are investigated using finite element analysis. Analytical studies are conducted on laminated beams and plates containing various sizes and locations of delamination. Special attention is focused on the vibration response corresponding to higher mode numbers, that is, in the intermediate frequency regime (<1 0kHz). Only the flexural vibrations are considered due to the greater influence thnt delaminations have on this mode of vibration, and sines it is the predominant mode in this frequency regime. Based on the results of this study, a methodology for determining the size and location of damage is suggested with the use of embedded piezoelectric sensors and actuators. Work is currently in progress to develop a health monitoring system for determining the presence and location of damage in a composite panel. The system works by exciting piezoelectrics embedded into the structure with broad band energy and monitoring changes in the structural response. Pattern recognition techniques are then used to identify structural defects,

INTRODUCTION

When a composite plate is subjected to long term mechanical loading (fatigue), thermal cycling or impact loading, damage in the form of mrrtrix cracking and delamination occurs, This type of damage is usually not visible and can severely reduce both the strength and stiffness of a composite material and therefore alter the vibrational response of the structure. While a number of damage evaluation techniques have been proposed, the approach used in practice is dependent upon the type of damage expected Ultrasonic testing (Williams and Lampert, 1980) is used for the detection and assessment of delamination in composite materials and has recently been investigated with scanning laser acoustic methods, This non-contact monitoring technique has been employed by McKie and Addison (1992) to study contoured composite parts for detecting impact damage and by Huang and Achenbach (1992) with a dud-probe differential laser interferometer for monitoring local wave speeds. Acoustic emissions has shown promise for monitoring the evolution of cracks and fiber fractures in a composite system as demonstrated try Gorman (1993) on polymeric materials and by Tiwari 8nd Henneke on ceramic materials (1992), Influence of damage in the form of matrix cracking and delamination on changes in coefficient of thermal expansion coefficient and o residual compressive strength has also been recently investigated by Mitrovic and Carman (1995) on woven composite systems. While some of these methods are very effective in detecting damage, many arc expensive, limited to specialized inspection sites, or require. time consuming scanning of the whole surface On the other hand, in-situ measurement of dynamic charm teristics, such as nature] frequencies, is a more convenient method for detecting damage in large structures (Adam.. and Cawley, 1985). Damage is typically inferred from shifts in natural frequencies.

The natural frequencies and mode shapes corresponding to the transverse vibrations of anisotropic plates can be determined by either exact or approximate analytical methods. Solutions for rectangular anisotropic plates subjected to different boundary conditions can be found in (Whitney, 1987). These solutions are based on classical plate theory where only low frequency-long wave length modes (i.e. plate thickness is sr.nail in comparison to the wave lengths of vibrations) obeying the Kirchoff deformation hypothesis are studied. For higher frequencies, the wave lengths are short in comparison to the thickness of the plate and transverse shear deformation and rotary inertia must be included Refined theories (first rrnd higher orders shear deformation theories) that include these effects can be found in Whitney (198'/) and Reddy and Khdeir (].989).

The effect of delaminations on the dynamic response of composites has been studied analytically and experimentally by a number of researchers. Cawley and Adarns (1979) detected various types of damage in composite plates, including holes, saw cuts and impact damage, by measuring the changes in lower structural natural frequencies. Tracy et al. (1985) investigated changes in the first 25 natural frequencies of impacted composite plates with free boundaries and reported reductions in frequencies for selected mode shapes. Reddy et al. (1984) studied both analytically and experimentally the influence of prescribed delaminations on vibration response of composite plates. While there have been studies on damaged plates, the vast majority of work has focused on the dynamic response of composite beam structures (Tracy and Pardoen, 1989, Mujumdar and Suryanarayan, 1988, and Stamos et al. ,1 992). These efforts used engineering beam theory to model *the* delamination by dividing the beam into four separate segments, each characterized by different bending and extensional stiffnesses. Keilers and Chang (1995) used built-in piezoelectrics sensors and actuators to experimental ly detect delaminations and estimate their size and location in composite beams. However, while a number of researchers have investigated the shifts in natural frequencies, they have typically limited their studies to the lower order modes of vibration.

Oru objective is to develop a methodology which is sufficientl y sensitive to detect damage, such as delamination, in advanced composite materials. It is our understanding that intermediate and high frequency ranges provide more opportunities for developing a structural health monitoring system than conventionally employed low frequency regimes. By comparing natural frequencies obtained on a baseline structure with ones measured after a certain time of service, information about the induced damage can be obtained. This approach is currently being investigated using a network of distributed piezoelectric actuators/sensors to detect changes in structural vibration signatures. This kind of health monitoring system *works* on a pattern recognition technique to identify the structural defect. Training of the neural network can be accomplished experimentally, however, an analytical model can also be used to shorten the time and resources required. In this study we propose to use a finite element approach as a method to train the neur al network. The choice of this numerical method is based on the fact that closed form solutions for delaminated plates do not exist

ANALYTICAL MODELING

The general purpose finite element computer code PATRAN was used to model a plate containing a simulated delamination. Two sets of analysis were performed to evaluate the influence of delamination on vibration response; one for composite beams and the other for composite plates, 10 simplify the modeling approach, only a single midplane delamination was studied. This delamination has the largest impact on a plates natural frequencies as shown by Mujumdar and Suryanarayan (1988).

Composite Beam Analysis

Finite element analysis of a composite beam specimen was performed using 4800 quadrilateral plain strain elements, that is 8 elements through the thickness and 600 elements through the length of the beam (see Figure 1) The physics of the problem justifies the plain-strain assumption, since the width of the beam is much longer than the beam thickness. The material Proper-ties are uniform and orthotropic.

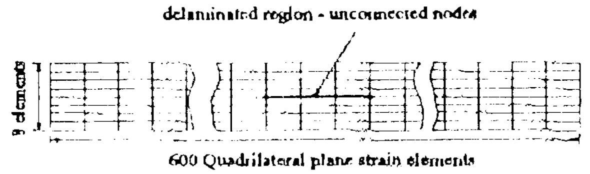


FIGURE 1. FINITE ELEMENT MODEL OF A BEAM

A midplane delamination is incorporated in the model by simply disconnecting *the* layers of nodes in the region corresponding to the simulated delamination length. In order to ensure that physically impossible mode shapes did not occur (discussion to follow later), and to simulate the contact forces which develop between the layers, spring (bar) elements were initially used to connect the nodes between delaminated layers. However, the natural frequencies obtained using this methodology are dependent on the spring (bar) stiffness, and this method did not prevent the non-physical mode shapes from occurring. This later fact was due to rotation Of the spring element connecting the delaminated layers. Therefore, the modeling approach adopted was disconnecting the nodes between two delaminated layers.

Composite Plate Analysis

Finite element analysis of a composite plate was performed using 1600 four-noded quadrilateral shell elements (QUAD/4/0) which have five degrees of freedom at each node in the local coordinates. This element implements a 'classical' laminate theory, so it is well suited to modeling thin strolls (PATRAN User Manual, 1990). Also, the properties of a ply and the stacking sequence can be directly input to the model, with extensional/bending stiffness terms automatically calculated

A few different approaches for simulating the midplane delamination were investigated, At first, the delamination was incorporated into the finite element model by replacing specific 16 ply undamaged elements (full plate thickness) with an element consisting of only the upper delaminated region, that is only 8 plies in the delaminated region. In the limit as the delamination grows through the entire plate, this approximation provides the correct solution to the vibration response of a delaminated plate However, the results of simulations performed in this study show that this approach tends to substantial ly overpredict the reductions in natural frequencies. Therefore, more accurate simulations were required. This was accomplished by replacing the 16 ply undamaged elements in the delaminated region with two layers of plate elements consisting of only half of the plate thickness. These 8 ply elements, while occupying the same volume, were connected to two independent layers of nodes (see Figure 2). At first, spring elements were used to connect the nodes between these two layers in order to simulate the contact forces which could develop. However, as stated previously, this was not successful. Consequently, the model utilizing the two layers of unconnected plate elements was used

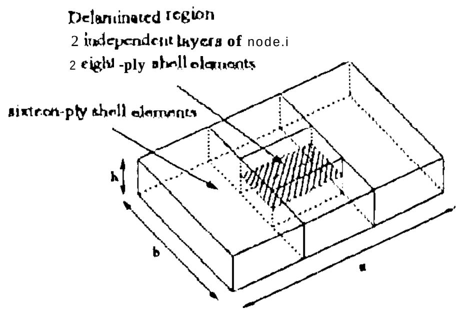


FIGURE 2. FINITE ELEMENT MODEL OF A DELAMINATED PLATE

It should be pointed out that the main objective of this part of the research was to investigate the changes of natural frequencies and mode shapes in the intermediate (<10kHz) frequency regimes. This required a fine mesh size to accurately depict the response of the plate. Comparisons made between a 4000 element mesh and a 1600 element mesh containing a delaminated region revealed no discrepancies in the first 100 natural frequencies. Also, the results of this analysis were compared with the analytical solutions available in the literature (Whitney, 19x7) for undamaged plates clamped all around, with less than 1% error observed for the first 100 natural frequencies. This indicates that the adopted mesh is of sufficient size to resolve these natural frequencies.

MATERIAL SYSTEM

The material system used in this study is an AS4/3501 -6 graphite/epoxy composite material. Mechanical properties for this transversely isotropic material are listed in Table 1. The analysis was performed on a $[0_2/-45/45_2/-45/0_2]_S$ laminate that was clamped on both sides (beam) and clamped all around the boundary (plate). Additional studies have been performed and some of them will be discussed later.

The following dimensions were employed in this study:

for a beam analysis: $l = 0.610$ m

for a plate analysis: $a = 0.280$ m, $b = 0.280$ m

TABLE 1. UNIDIRECTIONAL LAMINA (PLY) PROPERTIES FOR AS4/3501 -6

E_{11} (GPa)	139.1
E_{22} (GPa)	9.207
G_{12} (GPa)	5.28
ν_{12}	0.280
ν_{23}	0.202
ρ (kg/m^3)	1600
ply thickness (mm)	0.125

RESULTS AND DISCUSSION

As stated previously, only the flexural vibrations were of interest in this study. However, in intermediate and higher frequency regimes overlap occurs between the flexural and axial vibrations, thus the natural frequencies and mode shapes corresponding to the axial vibrations were ignored. Also, all modes studied have wavelengths of vibration substantially smaller than the plate thickness, thus justifying the omission of transverse shear deformation and rotary inertia from the analysis.

Previous research in this area (Mujumdar and Suryanarayan, 1988, and Tracy and Pardoen, 1989), using beam theory, demonstrated that the modeling approach employed influences the calculated vibration response, It was found that where the delaminated layers are free to deflect, and thus have different transverse displacements, the predicted reductions in natural frequencies overestimate experimental data (Mujumdar and Suryanarayan, 19Fig, and Chen et al., 1 995], These researchers suggested that the constraint of identical transverse displacements of two delaminated layers must be taken into account in order to prevent the non-physical mode shapes. Since the finite element modeling approach adopted in this analysis did not impose such constraints, the mode shapes obtained by this analysis were closely monitored and the natural frequencies corresponding to the non-physical mode shapes were simply removed. Typical mode shapes for both beam and plate analysis that represent the inadmissible vibration modes are presented in Figure 3

FIGURE 3. INADMISSIBLE MODE SHAPES FOR A) COMPOSITE BEAM AND B) COMPOSITE PLATE

AS can be seen from this Figure, inadmissible overlap occurs at certain points. Removal of these mode shapes was Simplified by the fart that the corresponding natural frequencies have the same value regardless of the destination location (for same delamination size). These 'local' mode shapes appear to resonate independently of the rest of the structure, and occur only when the wave length of vibration is of the same length as the delamination being studied. Possibly inaccurate, this observed behavior may serve as an indication of the local resonance previously investigated by Lin and Henneke (1990) using vibrothermography. These researchers demonstrated that by exciting a damaged composite plate in specific frequency regimes, local resonance occurs. This produces heat which can be detected by thermography. He-t generation should be maximized when the delaminated layers rub together, which would appear to represent the non-physical mode shapes. All other mode shapes in our investigation displayed identical displacements of the two delaminated layers, as expected for midplane delamination.

Composite Beam Analysis

The results of this part of' the analysis are presented in Table II and Figure 4. The composite beam studied was clamped on both sides and contained through the width midplane delamination. Three different centrally located delamination sizes were investigated spanning 10, 15 and 20% of Use beam total length. As can be seen (Table II and Figure 4) percentile changes in natural frequencies, for a specific delamination sire, exhibit large variations as long as the size of delamination is smaller than the wavelength of vibration Furthermore, the maximum change in frequency occurs when the two become of the same order of magnitude On the other hand, when the delamination exceeds the wavelength of vibration negligible changes are observed in percentile frequency reduction. For example, changes in the first five natural frequencies of 20% delaminated beam differ by as much as 18% while for the larger mode numbers little variations (less than 4 %) are present. Therefore, for high mode shapes, the natural frequencies of a beam change by approximately the same percentage, This is similar to a beam whose stiffness properties were uniformly changed.

The influence of delamination location (for delamination of 20% of the beam length) on frequency changes is presented in Figures 5 and 6. As can be seen, the changes in the first five natural frequencies are strongly dependent on damage location, It has been reported that the stress distribution in a vibrating structure is nonuniform and is different for each natural frequency (mode) (Adams and Cawley, 1985). The largest reduction in natural frequencies occurs when the edges of damaged region are located at the point of maximum stress (amplitude peak), while the effects on natural frequencies are smaller when they are close to the. point of zero stress for a given mode. However, frequency changes corresponding to higher mode numbers appear to be independent of damage position It appears that for mode shapes for which the damaged region is covered with more than one wavelength of vibration, the stress is 'evenly' distributed and the variation in natural frequencies are minimal While frequency changes for the first few modes have been reported and described in detail previously (Tracy and Pardoen, 1989, and Mujumdar and Suryanarayan, 1988), the independence of the frequency change for the higher mode numbers has not been observed to our knowledge,

TABLE II. FIRST 25 NATURAL. FREQUENCIES OF A COMPOSITE BEAM FoR DIFFERENT, CENTRALLY LOCATED, DELAMINATION SIZES

Mode	Undamaged	Damaged - center delamination					
	Frequency	10%		15%		20%	
#	Hz	Hz	% diff.	Hz	% diff.	Hz	% cliff
1	39	39	0.0	39	0.0	39	0.1
2	108	106	1.4	103	4,4	98	9.3
3	211	211	0,1	210	0.4	207	1,7
4	349	333	4.5	308	11.7	285	18.2
5	521	519	0,4	508	2.4	478	s,?,
6	727	670	7.8	623	14.3	609	16.2
7	968	937	1.2	900	7,0	820	15.3
8	1243	1122	9.7	1087	12.5	1082	12.9
9	1552	1508	2.8	1374	11.4	1317	15.1
10	1895	1712	9,7	1699	103	1632	13.8
11	2271	2153	5.2	1995	12.2	1982	12.8
12	2682	2452	8,6	2419	9.8	2251	16.1
13	3127	?893	7.5	2788	10.8	2721	13.0
14	3605	3336	'?.s	3196	11.3	3064	150
15	4117	3771	8.4	3721	9,6	3492	15.2
16	4662	4349	6.7	4083	12.4	4031	13.5
17	5241	4811	8.2	4726	9.8	4458	14.9
18	5853	5462	6.7	5161	11.8	5012	14.4
19	6497	6010	7.5	5767	11.2	5617	13.5
20	7175	6648	7.3	6406	10.7	6067	15,4
21	7885	7348	6.8	6953	11.8	6805	13.7
22	8628	7923	8.2!	7735	10.3	7371	14.6
23	9404	8799	6.4	8352	11.2	7996	1s.0
24	10211	9346	8.5	9076	11.1	8811	13.7
25	110s1	10327	6,5	9907	10.3	9435	14.6

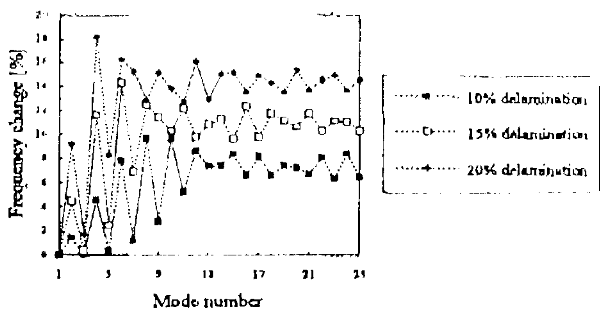


FIGURE 4. CHANGES IN NATURAL FREQUENCIES AS A FUNCTION OF DELAMINATION SIZES AND MODE NUMBERS

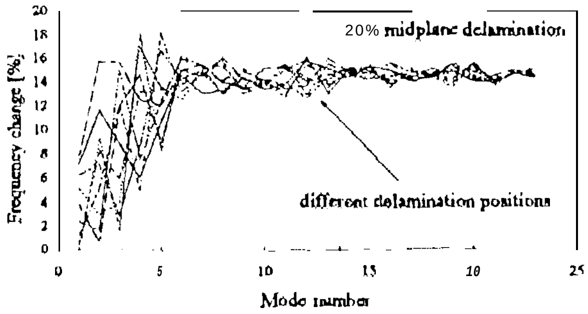


FIGURE 5. **CHANGES IN NATURAL FREQUENCIES AS A FUNCTION OF MODE NUMBERS FOR DIFFERENT DAMAGE, LOCATIONS**

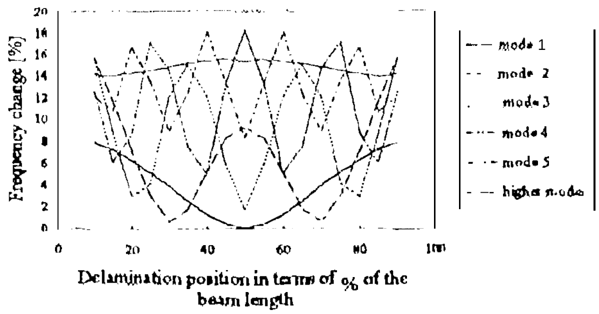


FIGURE 6. CHANGE IN NATURAL FREQUENCIES OF A COMPOSITE BEAM AS A FUNCTION OF SPANWISE LOCATION FOR DIFFERENT MODE NUMBERS

Therefore, the influence of delaminations on higher frequencies is insensitive to location and the frequency values are equally affected in percentage. These results leads us to suggest a new methodology for inferring the delamination size and location. That is, the delamination size could be inferred by focusing on frequency changes of higher mode numbers, since each delamination size produces different percentile changes (see Figure 7). Also, rather than focus on a specific frequency, a number of frequencies should be scanned and the average shift should be evaluated. This provides a qualitative value over a number of frequencies, and it dampens out discrepancies due to experimental measurement errors. Once the size has been determined, emphasize should be placed on the. first few natural frequencies in order to deduce the location of the damage, since these modes are more sensitive to damage location.

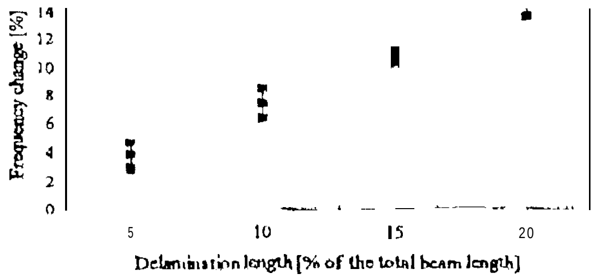


FIGURE 7. AVERAGE FREQUENCY CHANGES CORRESPONDING TO HIGHER MODES OF VIBRATION (20 - 25) **AS A FUNCTION OF DELAMINATION** SIZE.

Composite Plate Analysis

In this section the influence of a delamination's size and location on the dynamic response of a composite plate is investigated. The first 100 natural frequencies and mode shapes were evaluated to see if the higher modes are influenced more by damage than the lower ones, and to see if behavior regarding the location and size of damage, observed in beam analysis, is also valid for the dynamic response of composite plates.

Three different delamination sizes were investigated. They represent sizes likely to occur in service and cover 1, 4 and 6.25% of the panel area. A schematic representation of different locations is presented in Figure 8. That is, a total of ten different locations were investigated. Due to plate symmetry, results obtained for these ten locations should also be valid for other symmetric locations in the plate. Results of the finite element analysis show that delaminations spanning only 1 % of the plate area reduce natural frequencies less than 10/.. On the other hand 4% and 6.25% delaminations display substantially larger influence on dynamic response of the plate. For a delamination spanning 6.25% of the plate area, reductions in natural frequencies range from 2% to 11 % depending on the delamination position and mode number. While these percentile changes may seem small, the absolute frequency changes can be quite large for selected mode numbers, i.e. on the order of few hundred Hz.

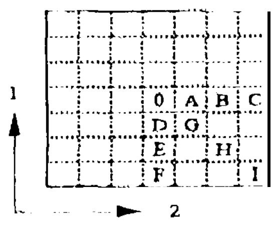
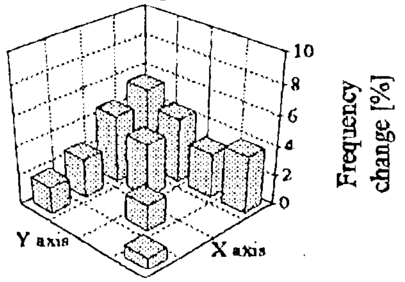


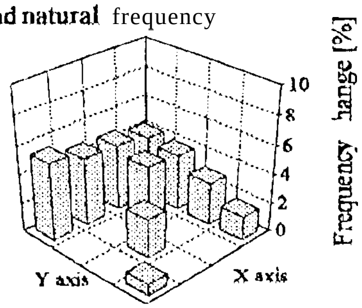
FIGURE 8. SCHEMATIC REPRESENTATION OF STUDIED DELAMINATION LOCATIONS IN A PLATE

In Figure Y changes in frequency as a function of location (only one quarter of a plate), for 6.25°/0 delamination, are presented for three different mode shapes. They correspond to the first two natural frequencies of a plate and the third one representing a higher frequency mode shape ($\omega_{baseline}$ = 9378 Hz). As can be seen (Figure 9a), the reduction in fundamental frequency changes between O, 8% and 5. so/o depending cm the location, The similar trend is ob.served for the second natural frequency (Figure 9b), but with a differed pattern in frequency changes. However, for the higher frequency range the changes seem to be relatively independent of damage location (Figure 9c). The maximum frequency reductions occur when the damage is located in the regions of a plate with higher strain energy. In lower vibration modes strain energy distribution is less uniformly distributed than in the higher ones, which causes larger frequency variations that depend on the damage location. Even for certain higher order modes there is a dependence on damage position, however, on the average percentile changes are much smaller than for the first few modes. Therefore, an approach similar to the one proposed for monitoring damage in beams can be implemented in order to infer the size of delamination.

a) First natural frequency



b) Second natural frequency



c) higher order frequency (-100)

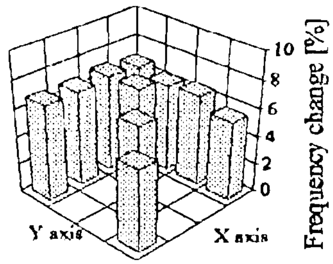


FIGURE 9. CHANGES IN FREQUENCIES OF SELECTED MODE NUMBERS (COMPOSITE PLATE) AS A FUNCTION OF DELAMINATION LOCATION

By comparing the mode shapes of the baseline and delaminated composite beams and plates additional information about the damage present in the composite cart be obtained It has been noted that most of the mode shapes have increased amplitude responses in the region where damage is, as compared to other parts of the laminate without delamination This localized behavior is understandable from a physical perspective, due to the lower flexural stiffness of the laminate in the delaminated region However, the region of influence of damage on the mode shapes is larger than the actual size of the delamination. Assuming that a distributed network of piezoelectric actuators and sensors is used, this localized behavior may lead to an 'amplified' response of specific sensors in the vicinity of damage, therefore signaling the location of damage.

EXPERIMENTAL MEASUREMENTS

Experiments arc currently underway to verify the results of the finite element analysis. In particular, a 0.305 x 0.305 m set of composite panels $[0_2/-45/45_2/-45/0_2]_S$ have been built and are currently being evaluated, The experimental tests consist of using an impulse hammer to examine natural frequencies occurring from 0-10 kHz and then verifying the results with the PZT sensor configuration. The HP3562 is used in conjunction with the STAR Structural Measurements Systems software and the PCB Electronics 086B03 Impulse Force Hammer to take impulse measurements. Tests are performed on both baseline and damaged plates with free boundaries. The impact induced damage covered approximately 50 x 50 mm, that is 2.7% of plate area. Only the results for the low frequency region are currently available, and they are presented in the Table III

A comparison of the results (Table III) shows some differences between predicted and experimentally obtained values. While there is a relatively good agreement for a plate without damage, the experimentally measured natural frequency at 1 02 Hz was not predicted by the analysis. Also, some closely spaced modes (1 st and ?.rid, and 4th and 5th) were compressed into a single mode which was not resolved experimentally. This actually resulted in an increase of the fundamental frequency and in disappearance of the second frequency. However, average predicted and experimentally observed percentile changes for the first ten modes are reasonably close.

TABLE III, NATURAL FREQUENCIES OF A BASELINE AND DAMAGED PLATE

Results of FEM analysis			
Mode number	no damage ω [Hz]	damaged ω [Hz]	% reduction
1	77	76	1.3
2	84	82.5	1.8
3			
4	179	177	1.1
5	182	1.79	1.6
6	222	?,2.1.7	0.1
7	256	254.6	0.5
8	333	331.5	0,4
9	377	369.9	1.9
10	472	464.9	1.5

Experimental results			
Mode number	no damage ω [Hz]	damaged ω [Hz]	% reduction
1	75	77	-2.6
2	86		
3	102	102	0,0
4	178		
5	187	186	0.5
6	204	203	0.5
7	274	268	2.1
8	339	338	0.3
9	374	370	1.1
10	471	470	0,2

A series of tests were also performed on composite plates containing piezoelectric sensors and actuators. This part of the experimental study involved much wider frequency range (up to 1,00 kHz) for detecting the presence, severity, and location of damage. Six 6.35 mm - diameter (0.2.5") PZT ceramic disks were embedded in a 0,33 by 0.635 m (13" by 25"), 16 ply graphite/epoxy panel $[0_2/\text{-}45/45_2/\text{-}45/0_2]_S$. The panel was clamped around the edges by a series of fastening screws. Figure 10 shows the layout of the transducers and the screw locations on the test panel. PZT #1 was used to send out a periodic chirp signal swept in frequency from O - 100 kHz. PZT #2 - #6 were placed in sensing mode in order to measure the structural vibration response. The sensor data was sampled at 2?50 kHz and downloaded from a signal analyzer to a PC using a National Instruments IEEE-488 interface board

FIGURE 10. PZT LAYOUT ON COMPOSITE PA

A series of "baseline" measurements were taken on an undamaged panel. Boundary failure was simulated by loosening screws along the boundary. Figure 11 compares two power spectrums, one from the baseline (healthy) case and the other from a damage case where 3 consecutive screws were loosened. As can be seen, there is a shift in magnitude and frequency with damage.

FIGURE 11. PSD OF BASELINE AND 3 LOOSENED SCREWS (ACTUATOR 1, SENSOR 6)

In order to quantify the relative change between the baseline and damage case, the *correlation coefficient*, CC, can be calculated:

$$CC = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \quad (1)$$

where x and y are the baseline and damage time signals, respectively, and i runs over the number of time data points. The range of correlation coefficient is from 0 for no correlation, to 1 for perfect shape conformity. Uniform changes in magnitude or scaling do not effect the value of CC. Figure 12 shows the trend is towards less correlation as more screws are loosened. Note that the baseline signal recovers to a correlation of almost 1 when the screws are re-tightened.

FIGURE 12. CC PLOT FOR LOOSENED SCREWS (ACTUATOR 1, SENSOR 6)

Another way to quantify the effect of damage is to calculate a feature referred to here as the *sumdelta*:

$$Sumdelta = \sum_{i} abs(y_i - x_i) \quad (2)$$

where i is any consecutive series of points within the power spectrum It can be calculated over any particular frequency band of interest. Figure 13 shows the plot of the sumdelta from 10 . 100 kHz. The change in power from the baseline increases as more screws are loosened.

FIGURE 13. SUMDELTA PLOT FOR LOOSENED SCREWS (ACTUATOR 1, SENSOR 6)

Delamination tests were also performed. The frame on the right side of the panel was removed and a delamination was created by driving a thin wedge into the edge of the panel at the mid plane as shown in Figure 14. Figure 15 shows the cumulative sumdelta from 10- 100 kHz for each sensor. In order to compare data between sensors, the sumdelta for each sensor has been normalized by their own baseline signal power. Note that the sensors closest to the damage, #3 and #6, experience the largest percentage change in signal strength over the selected frequency band Similar results have been observed for other types of damages such as holes, impacts, and boundary failures.

FIGURE 14. DELAMINATION LOCATION IN COMPOSITE TEST PANEL

FIGURE 15. NORMALIZED SUMDELTA FOR DELAMINATION

CONCLUSIONS

The influence of damage on vibration response for a specific composite laminate has been investigated both analytically and experimentally. Results suggest that by monitoring changes in natural frequencies and mode shapes in the intermediate and higher frequency regimes, valuable information about the present damage can be obtained. Work is currently ongoing to develop a health monitoring system containing embedded piezoelectric actuators ond sensors. Experimental results demonstrate the ability of such a system to detect the presence, severity and location of damage in structures by monitoring structural vibration changes over a wide frequency range.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of" •"•"

The part of this study that was conducted by California Institute of Technology was performed under a contract with NASA

REFERENCES

Adams, R.D. and P. Cawley, "Vibration Techniques in Nondestructive Testing," *Research Techniques in Nondestructive Testing*, Vol. 8, Edited by R.S. Sharpe, Academic Press, (1985), pp. 304-360.

Cawley, P. and R.D. Adams, "The Predicted and Experimental Natural Modes of Free-Free CFRP Mates," *Journal of Composite Materials*, 12, (1978), pp. 336-347,

Cawley, P. and R.D. Adarns, "A Vibration Technique for Non-Destructive Testing of' Fibre Composite Structures," *Journal of Composite Materials*, 13,(1979), pp. 161-175.

Chen, H -P., J.J. Tracy and R. Nonato, "Vibration Analysis of Delaminated Composite Laminates in Prebuckled States Based on a New Constrained Model," *Journal of Composite Materials*, 29 (2), (1995), pp. 229-256.

German, M., "New Development in Acoustic Emission for Experimental Mechanics," *Proceedings of SEM Conf, Dearborne MI*, 1993, pp. 1099-1106.

Huang, J. & J.D. Achenbach, "Measurements of Local Surface Wave Speeds by a Dual-Probe Laser Interferometer," *Rev. Prog. in Quant. NDE*, V.11a, pp. 593401, 1992.

Keilers, C. H., and F.-K. Chang, "Identifying Delaminations in Composites Using Built-in Piezoelectrics: Part J - Experiments, Model Development, and Verification", *Journal of Intelligent Materials and Systems*, 1995.

Lin, S.S. and E.G. Henneke, "Analytical and Experimental Investigations of Composites Using Vibrothermography", *Composite Materials: Testing and Design (Ninth Volume}, ASTM STP 1059*, S.P. Garbo, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 417-434.

McKie A.D. & R.C. Addison, 'Inspection of Components Having Complex Geometries using Laser-Based Ultrasound," *Rev. Prog. in Quant. NDE*, V.11a, pp. 577-585, 1992.

Mitrovic M. arrd G.P. Carman, "Effect of Fatigue Damage in Woven Composites on Thermo-Mechanical Properties and Residual Strength", Accepted for publication in *Journal of Composite Materials*, February 199S.

Mujumdar, P.M. and S. Suryanarayan, "Flexural Vibrations of Beams with Delaminations," *Journal of Sound and Vibration*, Vol. 125, No. 3 (1988), pp. 441-461.

PATRAN, A Division of PDA Engineering, P/FEA User Manual, Release 2,5, October 1990

Putcha, N S. and Reddy, J.N., "Stability and Natural Vibration Analysis of Laminated Plates by Using a Mixed Element Based on a Refined Plate Theory", *Journal of Sound and* Vibration, Vol. 104, No. 2 (1986), pp. 285-300.

Reddy, A.D., L.W. J@.Field and K.S. Haag, "Influence of Prescribed Delaminations on Stiffness-Controlled Behavior of Composite Laminates", *Effects of Defects in Composite* Materiels, *ASTM STP* 836, American Society for Testing and Materials, 1984, pp. 71-83.

Reddy, J.N. and A.A Khdeir, "Budding and Vibration of Laminated Composite Plates Using Various Plate Theories", *AIAA Journal* 27 (12), (1989), pp. 1808-1817.

Stamos, B., Kostopoulos, V. and S.A Paipetis, "Identification Of Delamination by Eigenfrequency Degradation - an Inverse Problem", *AGARD Conference Proceedings* 530, (1 992), pp. 20.1 .2().7.

Tiwari, A. & E. G. Henneke II, In-Situ Acoustic-Ultrasonic (AU) NDE Technique To Monitor Damage In SiC/CAS Ceramic Composites", *ASTM, 2nd Symp. on Cyclic Deformation, Fracture, and Nondestructive Evaluation of Advanced Materials*, Nov. 16-171992, Miami.

Tracy, J. J.. D.J. Dimas and G.C. Pardoen, "The Effect of Impact Damage on the Dynamic Properties of Laminated Composite Plates", *Proceedings of the Fifth International Conference on Composite Materials*, San Diego, CA (June 1985).

Tracy, J.J. and G.C. Pardoen, "Effect of Delamination on the Natural Frequencies of Composite Laminates," *Journal of Composite Materials*, 23 (12), (1 989), pp. 1200-1216.

Williams, J.H. & N.R Lampert, " Ultrasonic Evaluation of Impact Damaged Graphite Fiber Composite," *Materials Evaluation*, Dec. 1980, pp. 68-72.

Whitney, J.M, *Structural Analysis of Laminated Anisotropic Plates*, Technomic Publishing Co., Lancaster, 1 987.